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Analysis and Flame Retarding Design of Combustibles in Nanjing Typical Historical Buildings

YOU Fei*, ZHU Shun-bing, HAN Xue-feng

College of Urban Construction and Safety Engineering, Institute of Fire Science and Engineering, Nanjing University of Technology, Nanjing 210009, China

Abstract

Historical buildings are non-renewable cultural resources with important historical, artistic and scientific values. Most of Chinese historical architectural structures are built by combustible wooden components like beams, columns, brackets and floors, and always contain flammable ornaments like paper articles, textiles and plastic products inside. Such buildings are easily endangered by fires. Field investigations were conducted on four typical Nanjing historical buildings - ChaoTian Palace, GanXi Former Residence, JiMing Temple and JingJue Temple. The status and distributions of internal combustibles like wooden, fabric, plastic, paint and daily-used articles were counted, surrounding environments were explored and thus the potential fire hazards were evaluated. For the safe conservation of historical buildings, accessible flame retarding systems (flame retardants and processings) were presented, measures to reduce fire loads were also given.

Keywords: historical building, combustible, flame retarding design, Nanjing

* Corresponding author. Tel.: +86-25-83239949; fax: +86-25-83239949.
E-mail address: yfei@ustc.edu.cn.

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1. Introduction

Chinese historical buildings are developed based mainly on wood structures and also materials like bricks, tiles and stones. Woods show advantages in many aspects: locally sampled, easily processed, widely adaptive to different climates, highly flexible, excellently antiseismic, and both functionally and artisticly designed and produced. However, the biggest problem for such buildings is potential fires due to the combustibility and flammability of woods themselves and internal ornaments.

With a deep accumulation of cultures and as ever onetime capital for ten dynasties, Nanjing in Jiangsu province is an important represent of Chinese historical civilization. Till the end of 2007, there are more than 2029 cultural resource spots, among which 298 ones are historical buildings. ChaoTian Palace, GanXi Former Residence, JiMing Temple and JingJue Temple are four typical bulidngs ever destroyed by fires historically (see Table 1).

Table 1. Brief Descriptions of Four Typical Historical Buildings in Nanjing

Title	Period	Basic Description	Historical Fire	Type
JiMing Temple	The Western Jin Dynasty	One of the oldest Buddhist temple. Mountain, water, wood and temple are integrated. Surroundings are much elegant. It was converted place for Buddhist rite in 1958.	Destroyed by military fires during Xianfeng period in Qing dynasty.	Religious building
JingJue Temple	The Ming Dynasty	Top mosque in Nanjing with a general area of 1650m^2. One of the biggest and oldest mosque among the Southeast coastal cities. Historical and cultural site under provincal protection, center of political, religious, cultural and external affairs for the Hui nationality and Mohammedanism.	Destroyed by fire just after established during Hongwu period in Ming dynasty.	Religious building
GanXi Former Residence	The Ming and Qing Dynasty	Historical and cultural site under national protection. The former residence of Ganxi, a famous scholar and local recorder in Qing dynasty. Covering over 10000m^2. Special in orientations, layouts, functions and ornaments.	No way to be investigated.	Civil building
ChaoTian Palace	The Qing Dynasty	Covering over 70000m^2. Typical palace architectural complex of Ming and Qing dynasty style preserved most completely in Jiangnan district. Real materials prevailing in arrangement, pattern and construct techniques.	Part buildings destroyed by war fires in the end of Ming dynasty; later always exposed to fires in Daoguang period in Qing dynasty.	Royal building

For the fire protection of historical buildings, the overall fire hazards can be reduced by flame retarding combustibles except for drafting out guidance outlines and utilizing modern fire protection systems.

2. The Fire Hazards of Nanjing Typical Historical Buildings [1]

2.1. High fire load and low fire resistant level

The main structural components (like bucket arch, beam, column, rafter, joist, roof boarding, floor, staircase and ceiling) of investigated buildings are manufactured from pine, fir and camphor woods. The woods are largely used and form high fire loads in well-ventilated spaces. Some woods are naturally aged and rotten by worms after long-term application to become dry, loose, porous and cloven. In such case their flammability is much enhanced. External surfaces of such components are only ornamented with a layer of paint and not specially protected by fire-proofing dope. In general, these historical buildings show a low fire resistant level of three or four. Fig 1 shows the field scenarios inside Nanjing typical historical buildings.

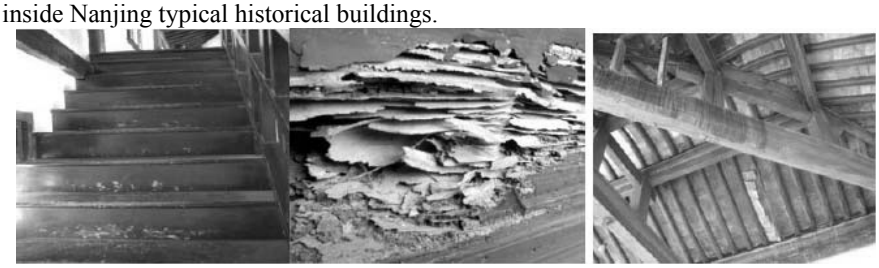

Fig. 1. Combustible Scenarios inside GanXi Former Residence (Left) and ChaoTian Palace (Middle and Right)

2.2. Narrow fire proofing space favoring massive burning

The investigated constructions are based on kinds of single buildings like quadrangle dwelling and cloister. Lanes, corridors and small squares are inserted. GanXi Former Residence is typical multi-enterclose cilivillian dwelling with a informal name of “ninty nine and a half room”. The buildings are most constructed symmetrically and

displayed along horizontal and vertical axes. Fire proofing spacings are thus lack and contribute to the fire spread. Neighboring wood structures can be burned in large areas. Fig 2 gives the overall distribution scheme of typical buildings.

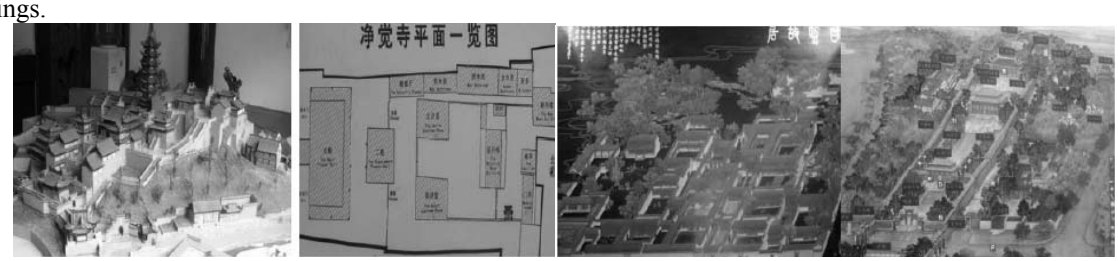

Fig. 2. Overall Distribution Scheme of JiMing Temple, JingJue Temple, GanXi Former Residence and ChaoTian Palace

2.3. Extensive distribution of combustible and flammable decorative materials

Many combustible decorative materials like paints, color drawings, folding screens, wall pictures and draperies are involved in investigated historical buildings especially in the the hall of avalokitesvara buddhisatva of JiMing Temple. It is decorated with lanterns and colored hangings including plastic water lily lamps, fabric sutra streamer, purdah, dried flower and color waxes. They are close to old wirings, electrical appliances and fire sources. Once caught fire, cubic burning would be formed instantly. In JingJue Temple, people always gather to conduct weekend activities. Many carptes and grassmats are piled in the corridor regularly and easy to induce fires transferred from smoldering processes. Fig 3 show the real scenarios inside the typical buildings.

Fig. 3. Distribution Scenarios of Combustibles inside JiMing Temple (Left and Middle) and JingJue Temple (Right)

2.4. Dificient in construction design and site selection leading to difficult suppression

The investigated buildings are located at busy streets (like JiJue Temple nearby the nanjing confucius temple) or on mountain massif (like JiMing Temple). The buildings are surrounded by commercial shops and transportation is busy. Thus fire passages are occupied or disappeared. Some buildings even set up high doorsills and footsteps. Therefore, fire origins will be gathered, burning rate will be fast, temperature will rise quickly and finally large area fires will occur and hard to be suppressed.

3. Combustible analysis in Nanjing Typical Historical Buildings

3.1. Wood

Logs and boards cut to square are commonly used in historical buildings. Firs are most used in backlogs, also pine, cypress, and Phoebe nanmu are used. Their basic properties and primary applications are shown in Table 2.

Table 2 Basic Properties and Primary Applications of Commonly-used Woods in Historical Buildings

Wood	Basic Property	Main Application
Fir	Stable anticorrosive and anti? property, good aseismatic property, light deadweight and stable demension, hard to be wormy	Pillar, purlin, rafter, roof boarding and eave of wood frames for main halls, pavilions,terraces and towers
Pine	High rigidity, low cost, big flexibility; weaker anticorrosive and mothproof properties than firs, easy crazing and distorting	Not wildly used, crooked rafter and grass roof boarding inside a veranda with window
Cypress	Excellent material, straight texture, delicate structure, anticorrosive property	Wood tip in furnishing articles (or small woodwork), cage and matchboard door; plugboard; wood hammer; flat crossbeam
Camphor	Heavy deadweitht, high rigidity, good dimensional stability, hard to be wormy	Crooked rafter, sweeping, tube plate and bucket arch of crooked angle components and wooden carving (Buddha figure, beauty backrest and handrail)
Phoebe nanmu	Straight and clear texture, delicate structure, hard to be crazed and distorted	Column and beam in palace and top grate house hall
Ginkgo biloba tree	Hard to be distorted, delicate and glossy texture, easy to be carved	Furnishing, floor covering, inscribed board, mounting, signboard in main hall

Fir and pine woods are selected for most investigated buildings due to maintanence cost and material source. After long term air drying and decay, most of these wooden components show low moisture content, cracking and chalking behavior, ripping and dropping cover protective paints, and micro-porous structure (see Fig 4). Such structure contributes to good conditions for burning and fire spread.

Fig. 4. Weathered Wood in ChaoTian Palace (Left and Middle) and Weared Wood in GanXi Former Residence

3.2. Textiles

Textiles are much more used in religious buidings like JiMing Temple and JingJue Temple than those in ChaoTian Palace and GanXi Former Residence (see Fig 5). In the main room of JiMing Temple, the upper space has been occupied by water lily lamps made of plastic (low density polyethylene) and fabric (terelene and cotton blends) elements, cloth paintings are posted all round the walls, fabric cushions are covered on tables and chairs, and curtains are hung surrounding the Buddha figures. Besides, draperies are hung in each room, floor coverings are used in some halls. These fabric products are large in quantity and pose high fire hazard when they are distributed in the center of main hall. In the palace of JingJue Temple, there are large area combustible wool carpets.

Fig. 5. Internal Display of JiMing Temple (Left and Middle) and JingJue Temple (Right)

3.3. Paints and Coatings

Wooden columns, beams, corridors and roofs coated with vermeil and brilliant blue paints can be seen everywhere in investigated historical buildings (see Fig 6). These wood components are always sealed and protected by tung oil after being polished. Then kinfe coating of lime putty, grounding and painting are conducted. Paints are combustible since they contain organic film bases (alkyd resin, acrylic resin, chlorited rubber resin and epoxy resin), pigments, solvents and assistants. In addition, when paints craze, curl up, pulverize and drip after long time weathing, the moisture content can be reduced and the wood will be rotten by worms. Fire hazard will be largely enhanced.

Fig. 6. Refreshed Paints and Color Drawings in ChaoTian Palace

3.4. Articles for daily use

In the investigated buildings, some halls and rooms are used to live and work for daily protection. Many articles for daily use are involved in such spaces, especially those in GanXi Former Residence (see Fig 7). Tables, chairs, bedsheets, quilt covers, books and electrical appliances are all combustibles. Coal gas and liquified gas are potential ignition sources. Bedrooms and cookrooms show higher fire loads.

Fig. 7. Display of Articles for Daily Use in GanXi Former Residence

4. Flame Retarding Design of Combustibles

To reduce the combustion property and fire hazard, flame retarding design [2] is to select different flame retardants and processing schemes based on combustible levels and located surroundings for various materials. In the investigated buildings, such design is mainly for wood and textile components.

4.1. Wood

Flame retarding of wooden products in historical buildings can be conducted as follows:

(1) Utilizing traditional phosphorous and nitrogen fire retardant coating and treatment fluid to deal with timeber rafters and columns

Non-transparent fire retardant coating can char to form a protective layer for base material from heat and oxygen when exposed to fire. Fire retardant treatment fluid can fully immerse in base material. When exposed to fire, it form into film and absorb heat to increase the fire resistance. For the timeber rafters at the corridor top, fire retardant coatings can be brushed or sprayed onto the surface. For the decorative supporting columns in hall, treatment fluid can be selected to in the way of perforating and injecting. When the decorative columns in hall are maintained, fireproofing putty can be inserted between the covering layer and varnish layer of base material to play a role of internal heat barrier.

(2) Utilizing fire retarded wood components or those made of naturally fire resistant trees to replace original combustible ones

Fire retarded wood components can enhance the fire resistant level of base material. Fire resistant trees generally show high burning point, unique texture and compact porous microstructure. Thus, the fire endurance can be improved directly.

(3) Developing novel comprehensive fire retarding technique such as combining transparent fire retardant coating with light (mainly UV) radiation curing technique to form fast-shaped protective film

Radiation curing technique is a newly developed processing art for resins. Practically, liquid unsaturated resin solutions are radiated by UV and fluorescent lights. Molecules are intensified in short period under such high intensity rays and produce active free radicals or ionic radicals to incite polymerizing, crosslinking and grafting reactions. Liquid coatings are thus transformed to solid state in seconds and form good functional films. Radiation curing technique shows advantages in the following aspects: high production rate (generally in 1-10s), curing at

room temperature, low energy consumption, high solid content (almost 100%), no solvent, no harmless emissions, high reliability, fast drying, high strength, strong ornament effect, high rigidity and good anticorrosion level.

Transparent fire retardant coating for wood consists of expandable foaming base coating and decorative top coating. The former includes ammonium polyphosphate (APP), melamine (MA) and pentaerythrite. When it is exposed to fire, the coating expands quickly to a compact and uniform cellular or sponge-like carbonaceous foam layer. The layer can prevent both the external heat and air from the base material. The processing step is as follows: cleaning base material→filling up shallow pot hole→grounding→clearing off dust→blending binary coating components→brushing base coating→brushing top coating. Base material with obvious deficiency of uneven surface, crack and pitted surface should be filled and levelled up with fireproofing putty of quartz flour or barium sulfate flour.

When the above two techniques are combined, expandable radiation curing transparent fire retardatn coating based on main elements of phosphorous, nitrogen, silicon and transition metals can be developed and meet the overall requirement of ornament, fireproofing, recyclability, manufacturability, low cost and fast processing.

4.2. Textiles

Generally, fire ratings of textiles can be improved by finishing in three ways: dyeing exhaust process, flame retardatns combine with cellulose fibers through ionic or covalent forces and dissolve to obtain a long time endurance effect; stock solution process, flame retardants are added to spinning solutions directly and immerse the fibers without chemical bonds; copolymerization process, flame retardant function group can be connected to the polymer segments to obtain long time endurance effect.

Since the textiles in the investigated buildings are not much used, their materials are unitary, and their washing requirement are not that high, fire retardant solution can be applied for a short time endurance effect. The processing is [3]: dipping→laundry drying→oven drying or drying in the air; padding→oven drying; spraying→oven drying or drying in the air. For example, when a mixed systme of borax and ammonium borate is used at a mas ratio of 7:3, only 6-10% amount can bring good fire retardant level. In addition, fire retardant sols prepared by the hydrolysis of metal salts or metal alkoxy compounds can form gel protective layers inside and on the surface of textiles by immersing and curing. This is a promising novel technique.

5. Concluding remarks

The surrounding environments, and materials, distributions and current status of combustibles were investigated for four Nanjing typical historical buildings of ChaoTian Palace, GanXi Former Residence, JiMing Temple and JingJue Temple. Their overall potential fire hazards were analyzed. Results show that the most fire loads for these buildings are various wood components and internal textile products. Wood componts were simply sealed and protected by putty and paints. Bad conditions such as wearing and dripping are general in such buildings. Hence, the fire safety of wood components is much decreased. In such case, proper fire retardant processing techniques and developing novel chemical protection techniques like sol-gel processing art are proposed. For example, expandable radiation curing transparent fire retardatn coating based on main elements of phosphorous, nitrogen, silicon and transition metals can be developed. Fire retardant coatings for textiles can also be developed using sol-gel techniques.

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